

Disentangling Dark Matter Dynamics

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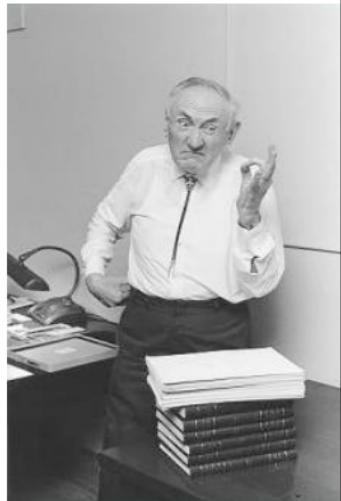
September 24, 2009

M. L. & Jay G. Wacker, arXiv: ---

Status of Dark Matter

Hints at non-trivial dark matter interactions

DAMA
PAMELA
ATIC
FERMI
WMAP Haze
INTEGRAL



Not your grandfather's dark matter candidate...

Outline

Non-trivial dynamics in dark matter sector?

Explanations for suppressed spectra

Composite dark matter models

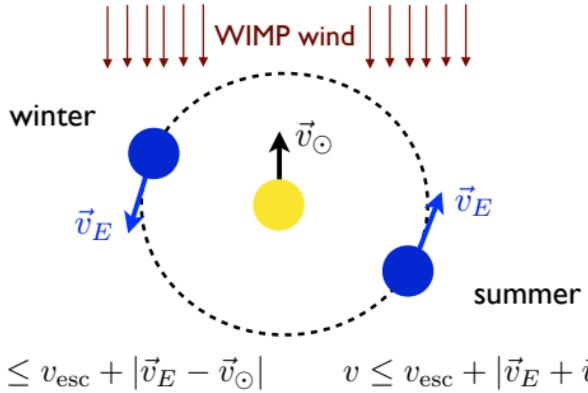
Experimental Prospects?

Uncertainties in halo profile

Direct Detection

Directional Detection Experiments

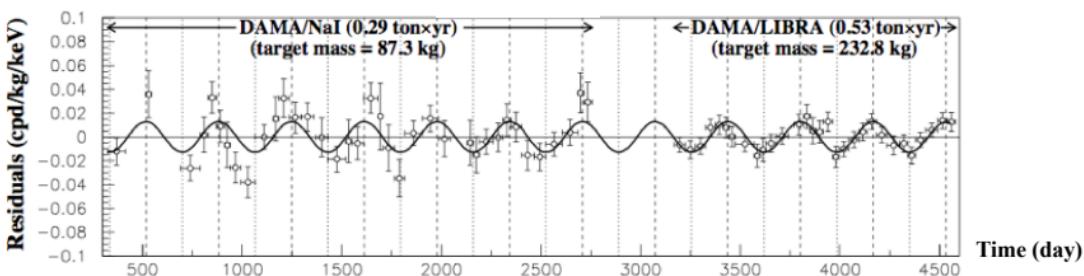
DAMA



Annual modulation in WIMP signal

$$\Phi_{\text{wimp}} = \sigma v$$

Modulation amplitude $\sim 2.5\%$ for elastic scattering



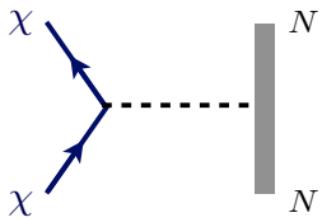
Direct Detection

Dark matter may scatter off of nuclei in detectors

Can measure recoil energy of nucleus

spin-independent

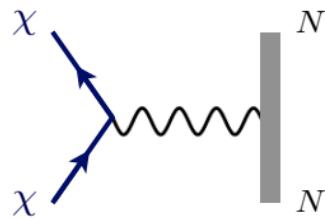
$$(\bar{\chi}\chi)(\bar{q}q)$$



$$\sigma_{\text{SI}} \propto A^2$$

spin-dependent

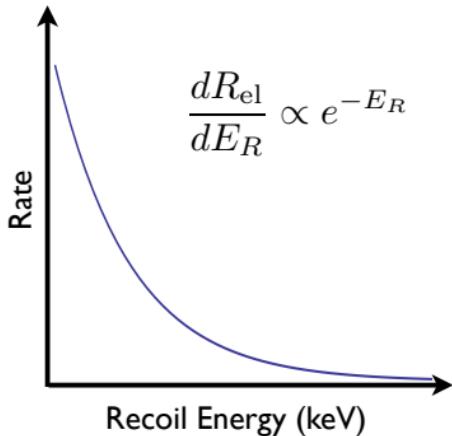
$$(\bar{\chi}\gamma_\mu\gamma_5\chi)(\bar{q}\gamma^\mu\gamma_5q)$$



$$\sigma_{\text{SD}} \propto \frac{J(J+1)}{J^2}$$

Direct Detection

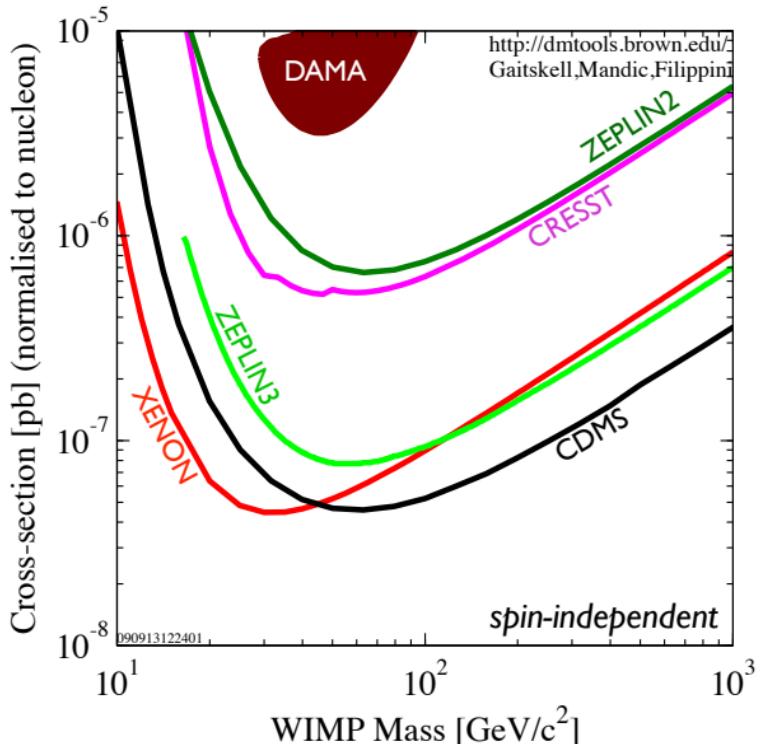
Experiments optimized to look for elastic scattering recoil spectrum



Experiment	Element	Signal Window (keV)	# Events	Exposure (kg day)
CDMS	Ge	10-100	2	174
XENON	Xe	4.5-45	24	122
ZEPLIN 2	Xe	14-56	29	225
ZEPLIN 3	Xe	11-31	7	127
CRESST	W	10-100	7	30

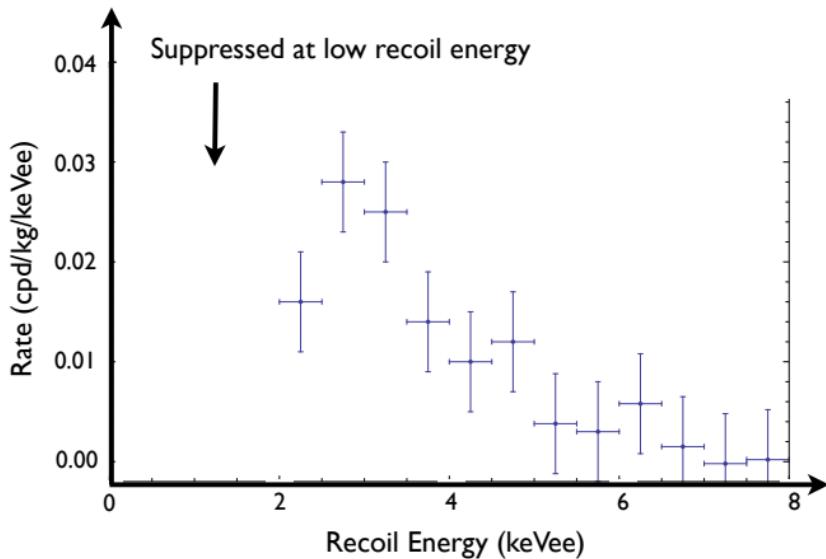
DAMA has 0.82 Ton Years!

Current Limits



DAMA

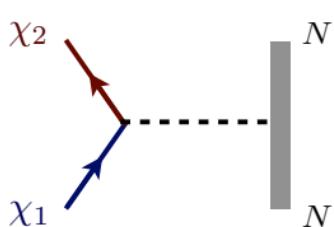
Modulation Amplitude



Inelastic Dark Matter

Dark matter has two nearly degenerate states

$$\delta m \sim (100 \text{ keV})$$



Threshold velocity necessary to scatter with energy E_R

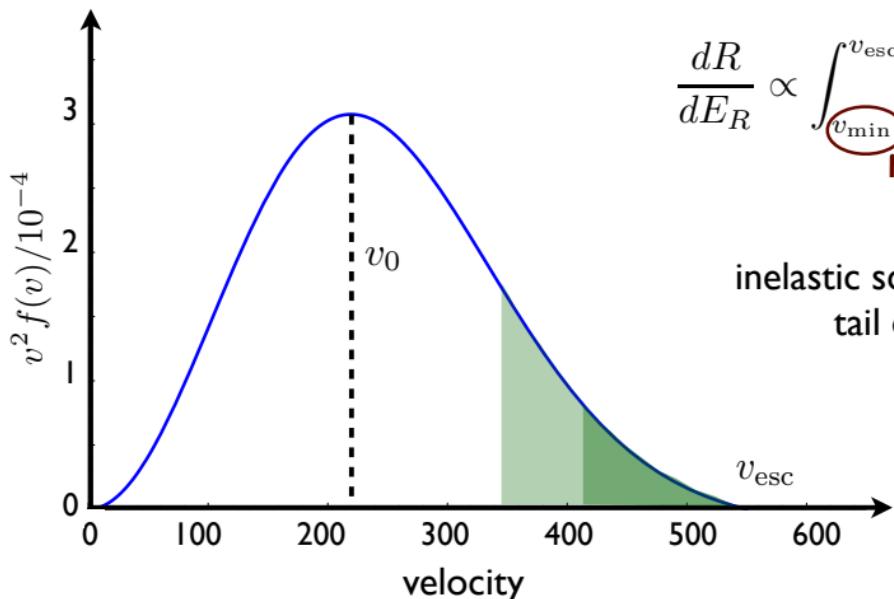
$$v_{\min} = \frac{1}{\sqrt{2m_N E_R}} \left(\frac{m_N E_R}{\mu} + \delta m \right)$$

Lighter nuclei, higher threshold

Tucker-Smith and Weiner (2001).

Scattering Rate

Scattering rate depends on halo profile

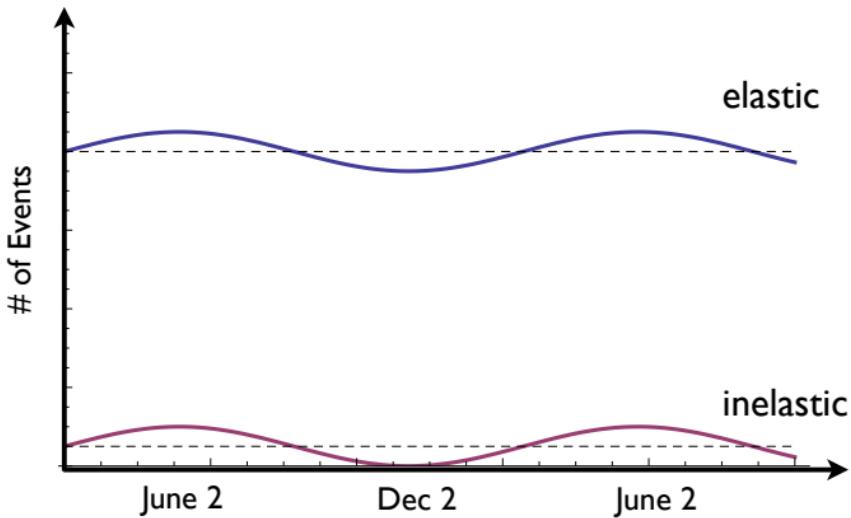


$$\frac{dR}{dE_R} \propto \int_{v_{\min}}^{v_{\text{esc}}} d^3v f(v) v \frac{d\sigma}{dE_R}$$

inelastic scattering sensitive to tail of distribution

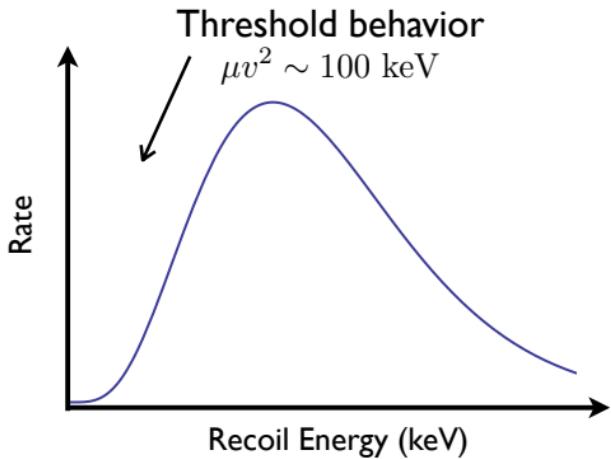
Modulation Fraction

Larger modulation fraction for inelastic dark matter
because absolute signal is smaller



Inelastic Dark Matter

3 Consequences



Scatters off of heavier nuclei
CDMS ineffective

Large recoil energy
XENON didn't look

Large modulation fraction
DAMA is sensitive

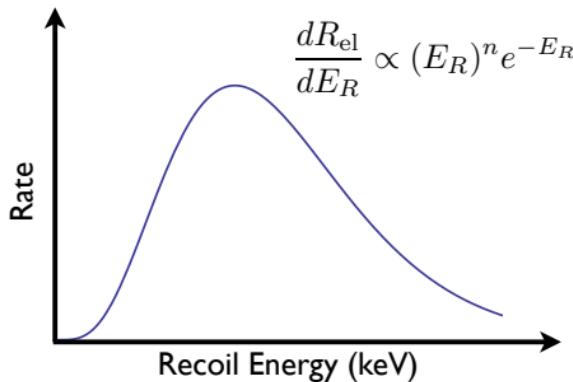
Dark Matter Form Factors

Feldstein, Fitzpatrick, and Katz (2009).
Chang, Pierce, and Weiner (2009).
Pospelov and Ritz (2003).

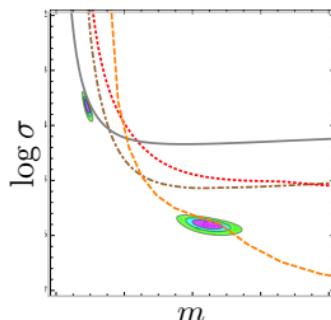
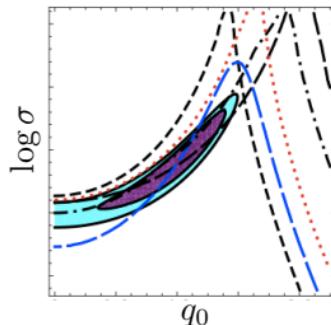
Can suppress low energy scattering

$$F_{\text{dm}}(q^2) = c_0 + c_1 q^2 + c_2 q^4 + \dots$$

$$q^2 \simeq m_N E_R$$



Best case scenarios



Inelastic Dark Matter

A new number to explain

$$\frac{\delta m}{m} \sim 10^{-6}$$

Sign of dark sector dynamics?

First of many splittings

New interactions to discover

Changes what questions are interesting...

Outline

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Composite Dark Matter

Alves, Behbahani, Schuster, and Wacker (2009).

New $SU(N_c)$ gauge sector confines at scale Λ_d

Two new quarks that form bound states

q_H q_L

spin 0



dark pion

π_d

spin 1



dark rho

ρ_d

Cosmology

Alves, Behbahani, Schuster, Wacker, 0903.3945.

A cosmological asymmetry

$$(n_H - n_{\bar{H}}) = -(n_L - n_{\bar{L}}) \neq 0$$

When $T \ll \Lambda_d$, dark matter is in
 $q_H \bar{q}_L$
bound state

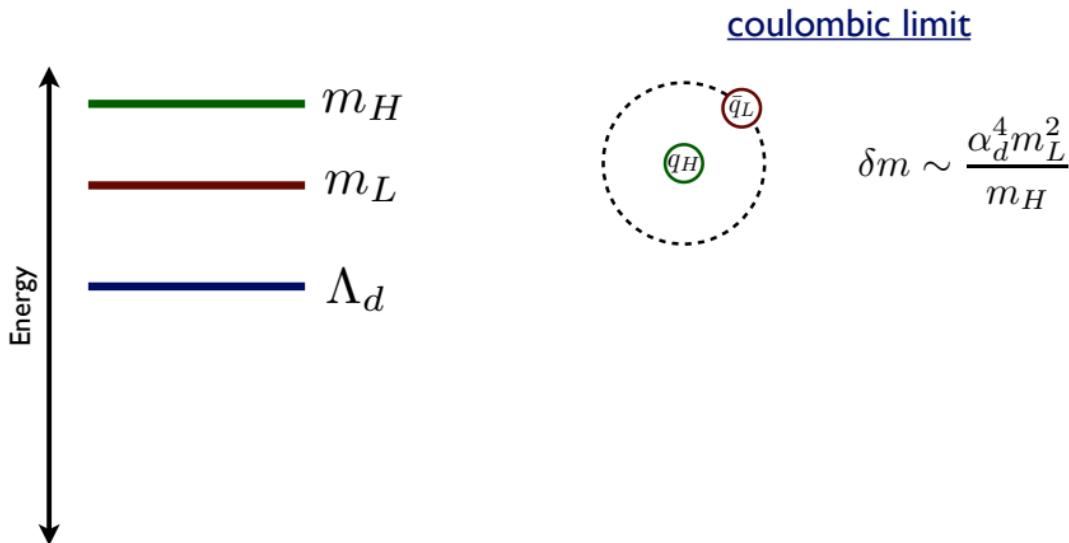
Spin temperature low

$$\frac{n_{\rho_d}}{n_{\pi_d}} = \exp(-\delta m/T_{\text{spin}})$$

Kinetically decouple late,
smaller spin temperature

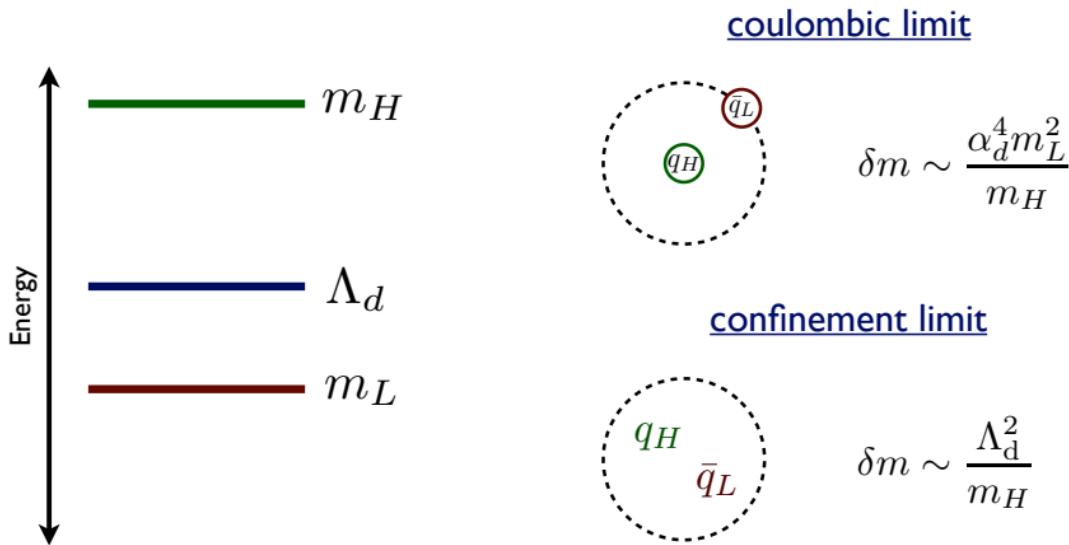
Composite Dark Matter

Mass difference in meson states arises from hyperfine splitting



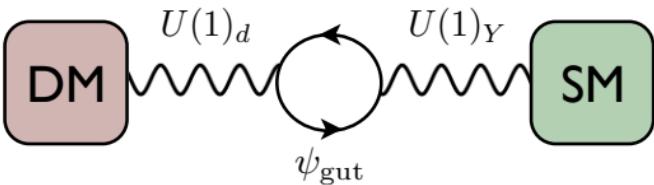
Composite Dark Matter

Mass difference in meson states arises from hyperfine splitting



Coupling to Standard Model

Kinetically mix $U(1)_d$ with $U(1)_Y$



$$\mathcal{L} = -F_d^2 - F_{\text{EM}}^2 - \boxed{\epsilon F_d F_{\text{EM}}} + m_A^2 A_d^2 + J_{\text{EM}} A_{\text{EM}} + J_d A_d$$

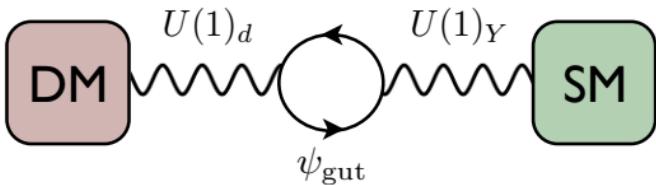
gauge boson mixing

Higgs $U(1)_d$ near the electroweak scale

$$\mathcal{L}_{\text{Higgs}} = |D_\mu \phi_d|^2 - V(\phi_d) \rightarrow m_A^2 A_d^2$$

Coupling to Standard Model

Kinetically mix $U(1)_d$ with $U(1)_Y$



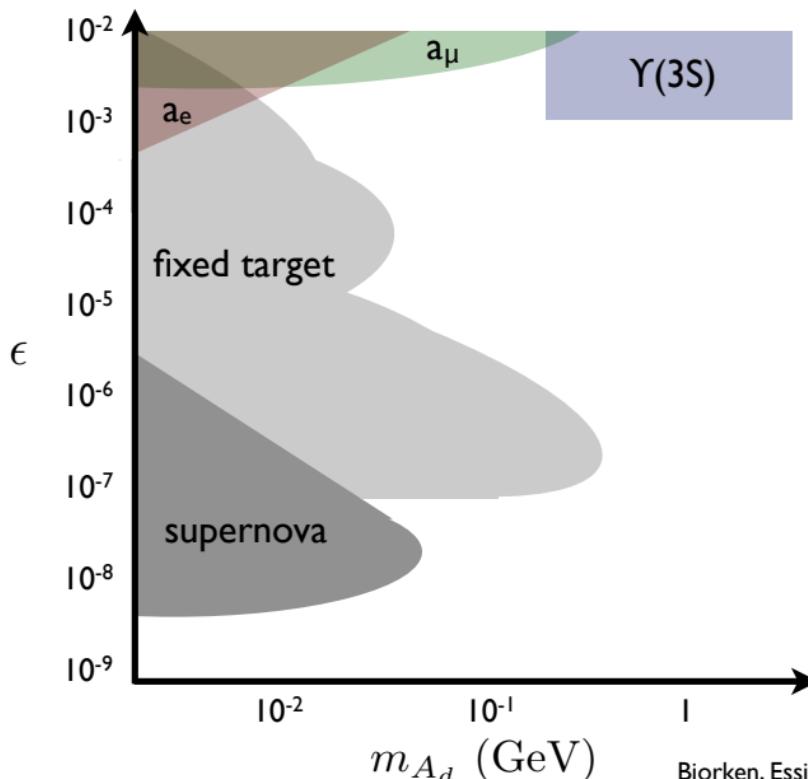
$$\mathcal{L} = -F_d^2 - F_{\text{EM}}^2 - \epsilon F_d F_{\text{EM}} + m_A^2 A_d^2 + J_{\text{EM}} A_{\text{EM}} + J_d A_d$$

redefine SM photon $A_{\text{EM}} \rightarrow A_{\text{EM}} - \epsilon A_d$

$$\mathcal{L} = -F_d^2 - F_{\text{EM}}^2 + m_A^2 A_d^2 + J_{\text{EM}}(A_{\text{EM}} - \epsilon A_d) + J_d A_d$$

$$\mathcal{L}_{\text{int}} \propto \epsilon J_{\text{em}}^\mu A_{d\mu}$$

Current Limits on ϵ



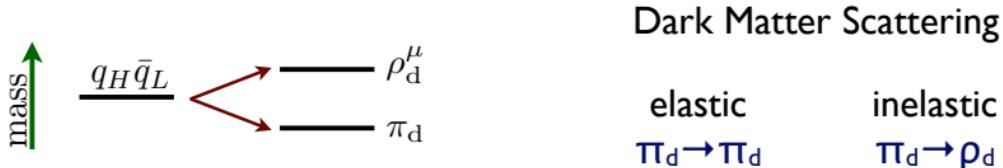
Pospelov (2008).

Reece and Wang (2009).

Bjorken, Essig, Schuster, and Toro (2009).

Effective Field Theory

Use EFT to describe interactions of mesons



spin 0 meson

$$\pi_d \rightarrow -\pi_d$$

spin 1 meson

$$\rho_{d\mu} \rightarrow (-1)^\mu \rho_{d\mu}$$

Parity of new gauge boson determines the allowed interactions in the effective Lagrangian

Dark Matter Current

Two choices for anomaly-free charges

Vector Coupling

$$J_d^\mu = \bar{q}_H \gamma^\mu q_H - \bar{q}_L \gamma^\mu q_L$$

Does not forbid quark masses

Axial-Vector Coupling

$$J_d^\mu = \bar{q}_H \gamma^\mu \gamma^5 q_H - \bar{q}_L \gamma^\mu \gamma^5 q_L$$

Forbids quark masses until $U(1)_d$ Higgsed

Axial Coupling

Elastic

$$\pi_d \rightarrow \pi_d$$

$$\frac{1}{\Lambda_d^2} \pi_d^\dagger \partial_\mu \pi_d \partial_\nu \tilde{F}_d^{\mu\nu}$$

dimension 6

velocity suppressed

Inelastic rate dominates:

Inelastic

$$\pi_d \rightarrow p_d$$

$$\frac{1}{\Lambda_d} \pi_d^\dagger \partial^\mu \rho_d^\nu F_{d\mu\nu}$$

fraction to scatter inelastically

$$\frac{R_{\text{el}}}{R_{\text{in}}} \simeq \frac{q^2 v_{\text{rel}}^2}{\Lambda_d^2} \frac{1}{F_{\text{halo}}} \simeq 10^{-4}$$

Nearly pure inelastic scattering

Vector Coupling

Elastic

$\pi_d \rightarrow \pi_d$

$$\frac{1}{\Lambda_d^2} \pi_d^\dagger \partial_\mu \pi_d \partial_\nu F_d^{\mu\nu}$$

charge-radius scattering

Inelastic

$\pi_d \rightarrow \rho_d$

$$\frac{1}{\Lambda_d} \pi_d^\dagger \partial^\mu \rho_d^\nu \tilde{F}_{d\mu\nu}$$

velocity suppressed

Elastic rate dominates:

$$\frac{R_{\text{el}}}{R_{\text{in}}} \simeq \frac{q^2}{\Lambda_d^2 v_{\text{rel}}^2} \frac{1}{F_{\text{halo}}} \simeq 10^8$$

Nearly pure elastic scattering

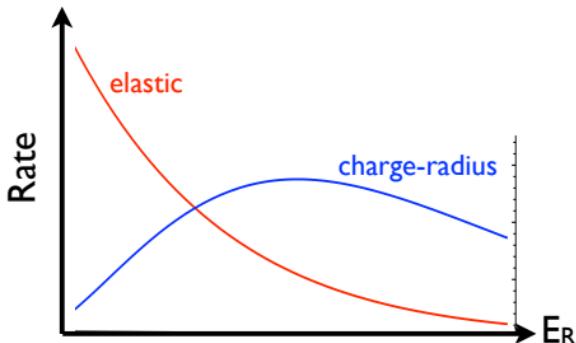
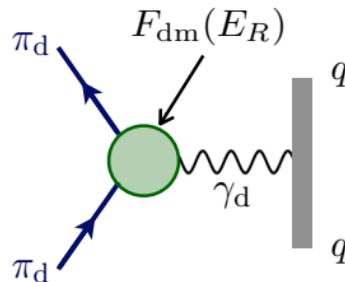
Charge Radius

Neutral composite states with charged constituents

Form-factor suppression from interaction with background field

$$\mathcal{L}_{\text{cr}} = F_{\text{dm}}(E_R) \bar{q} i e A_{\text{d}} q$$

$$F_{\text{dm}}(0) = 0 + r_c^2 E_R$$



Charge-radius scattering difficult to distinguish from inelastic scattering

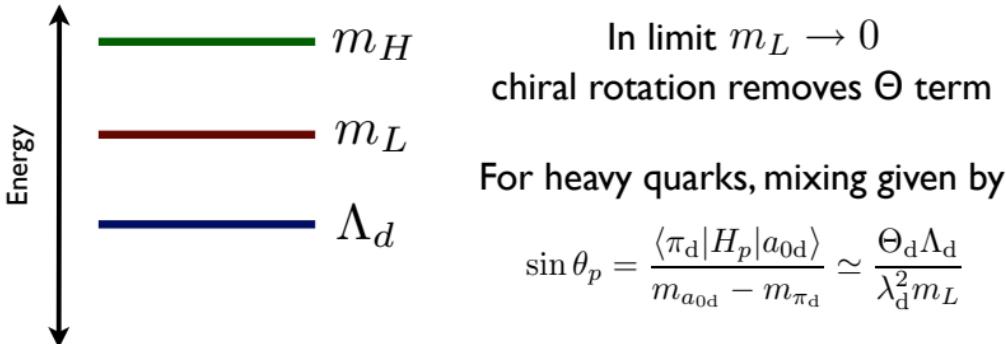
CP Violation

Θ term in dark QCD sector

$$\mathcal{L}_{\text{cpv}} = \Theta_d \text{Tr} G_d \tilde{G}_d$$

Not necessarily small

Leads to mixing between states of different parity
e.g. $\pi_d \leftrightarrow a_{0d}$



CP effects vanish as $m_L \rightarrow 0, \infty$...maximized when $m_L \simeq \Lambda_d$

Effects of Parity Violation

Admixture of vector and axial interactions

$$F_d^{\mu\nu} \rightarrow \cos \frac{\theta_p}{2} F_d^{\mu\nu} + \sin \frac{\theta_p}{2} \tilde{F}_d^{\mu\nu}$$

	<u>Elastic</u>	<u>Inelastic</u>
<u>Axial</u>	$\frac{1}{\Lambda_d^2} \pi_d^\dagger \partial_\mu \pi_d \partial_\nu \tilde{F}_d^{\mu\nu}$	$\frac{1}{\Lambda_d} \pi_d^\dagger \partial^\mu \rho_d^\nu F_{d\mu\nu}$
<u>Vector</u>	$\frac{1}{\Lambda_d^2} \pi_d^\dagger \partial_\mu \pi_d \partial_\nu F_d^{\mu\nu}$	$\frac{1}{\Lambda_d} \pi_d^\dagger \partial^\mu \rho_d^\nu \tilde{F}_{d\mu\nu}$

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<u>Vector</u>	$\frac{1}{\Lambda_d^2} \pi_d^\dagger \partial_\mu \pi_d \partial_\nu F_d^{\mu\nu}$	$\frac{1}{\Lambda_d} \pi_d^\dagger \partial^\mu \rho_d^\nu \tilde{F}_{d\mu\nu}$

Neither axial or vector, but elastic and inelastic interactions

Effects of Parity Violation

Admixture of vector and axial interactions

Axial

$$\frac{R_{\text{el}}}{R_{\text{in}}} \propto \tan^2 \frac{\theta_p}{2}$$

Vector

$$\frac{R_{\text{el}}}{R_{\text{in}}} \propto \cot^2 \frac{\theta_p}{2}$$

Any ratio of charge-radius elastic to inelastic scattering can be achieved by appropriate choice of mixing angle!

Can we discover small elastic contributions to scattering rate?

Outline

Non-trivial dynamics in dark matter sector?

Explanations for suppressed spectra

Composite dark matter models

Experimental Prospects?

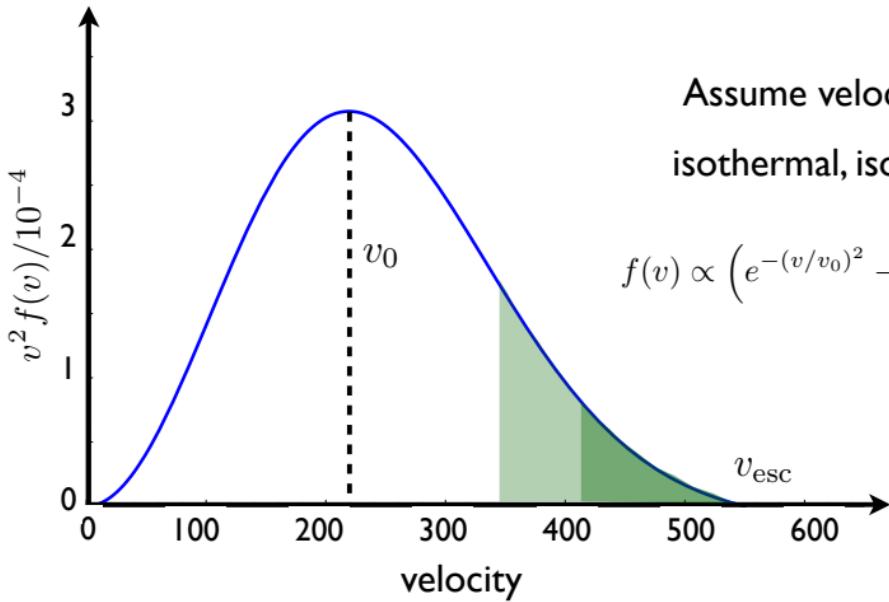
Uncertainties in halo profile

Direct Detection

Directional Detection Experiments

Standard Halo Model

N-body simulations indicate that density falls off more steeply at larger radii



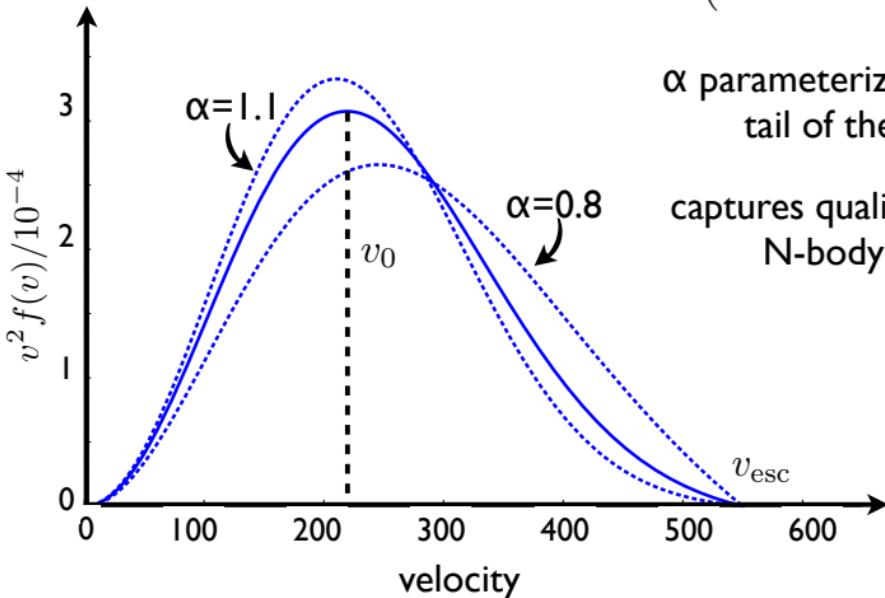
Assume velocity distribution is:
isothermal, isotropic, & Gaussian

$$f(v) \propto \left(e^{-(v/v_0)^2} - e^{-(v_{\text{esc}}/v_0)^2} \right) \Theta(v_{\text{esc}} - v)$$



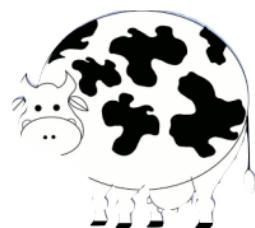
Modified SHM

$$f(v) \propto \left(e^{-(v/v_0)^{2\alpha}} - e^{-(v_{\text{esc}}/v_0)^{2\alpha}} \right) \Theta(v_{\text{esc}} - v)$$



α parameterizes variation in the tail of the distribution

captures qualitative behavior of N-body simulations



Setting Limits on Cross Section

Usually set limits on cross section per nucleon

Factor of A^4 to translate

iDM has non-trivial kinematics

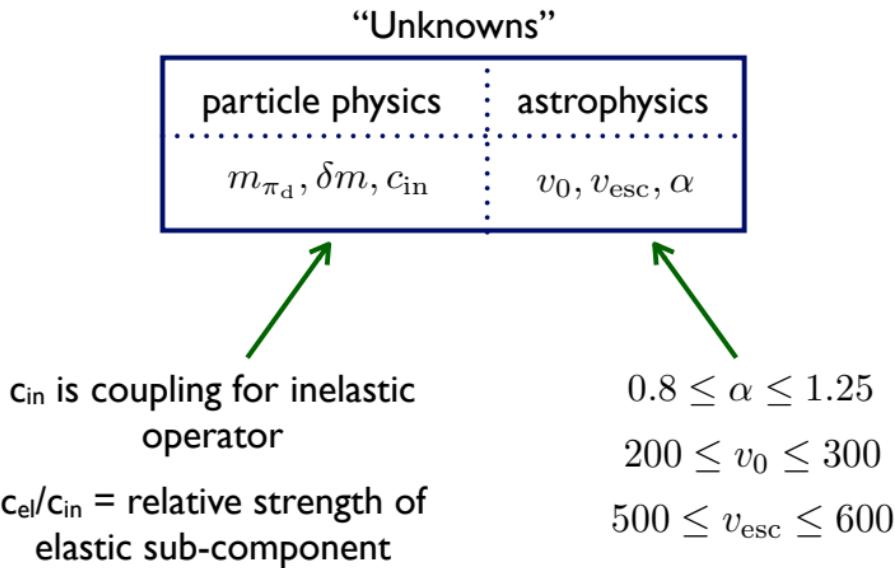
Light nuclei have *no* cross section

Should use particle physics parameters

$$\sigma \propto \frac{Z^2 \alpha_{\text{EM}}}{f^4} \qquad f^2 \simeq \frac{m_A^2}{c_{\text{in}} \epsilon g_d}$$

Marginalizing over Uncertainties

How do current experiments constrain parameters?



Marginalizing over Parameters

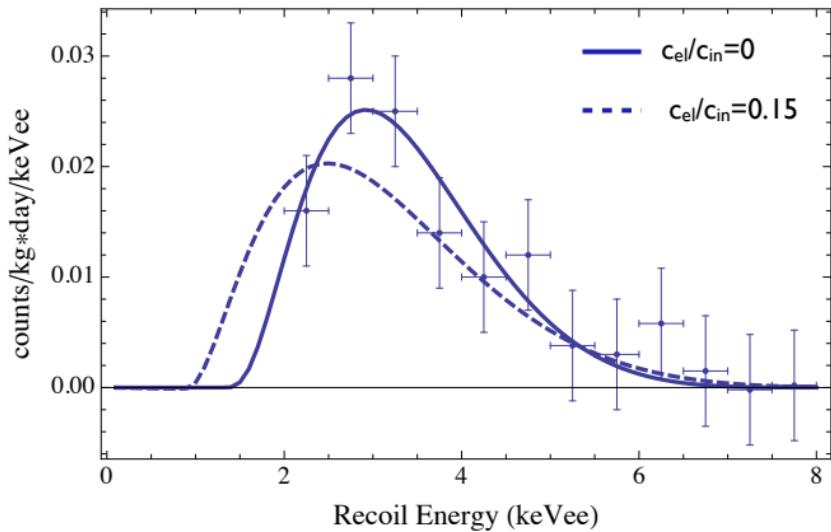
Minimize χ^2 over 6 parameters using results from direct detection experiments

$$\chi^2(m_{\pi_d}, \delta, f_i, v_0, v_{\text{esc}}, \alpha) = \sum_{i=1}^{N_{\text{exp}}} \left(\frac{X_i^{\text{pred}} - X_i^{\text{obs}}}{\sigma_i} \right)$$

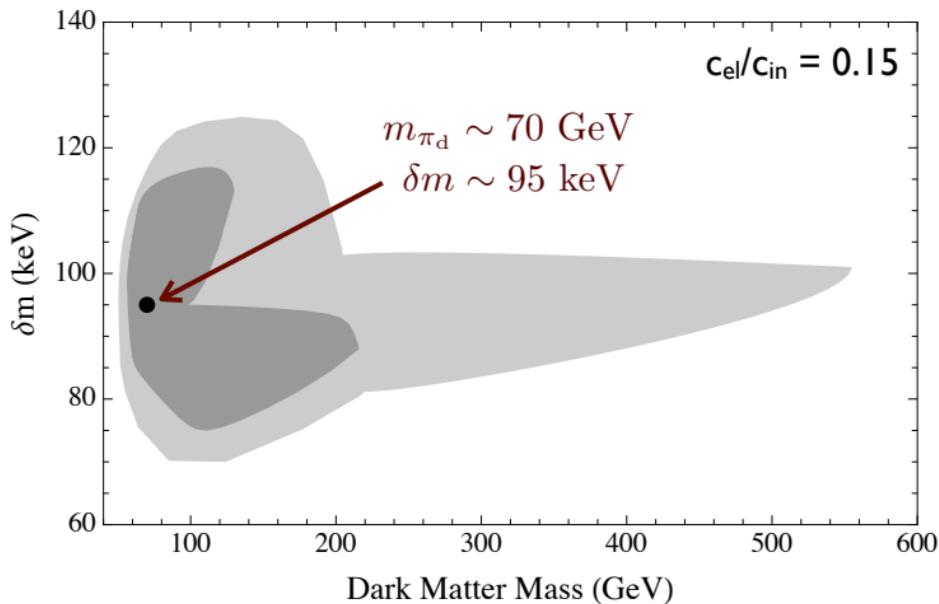
Fit to DAMA recoil spectrum

Require that theory predicts \leq number of events seen by each null experiment

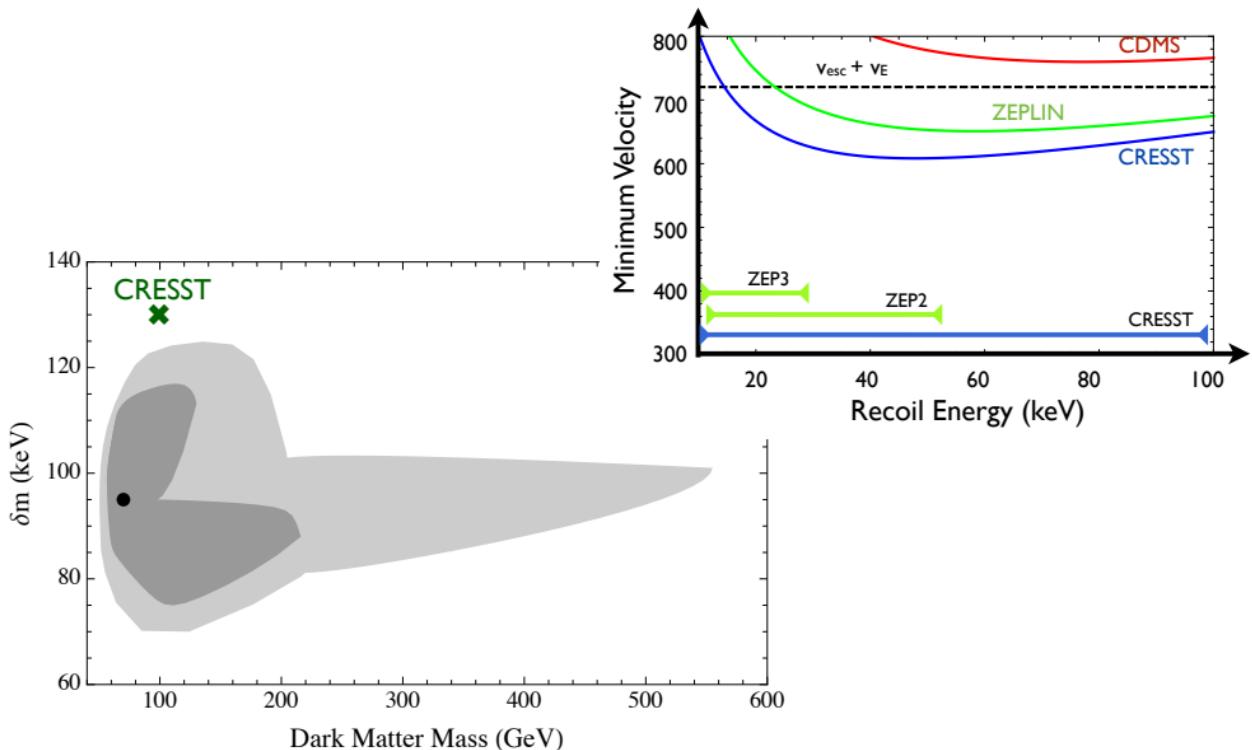
Modulation Amplitude



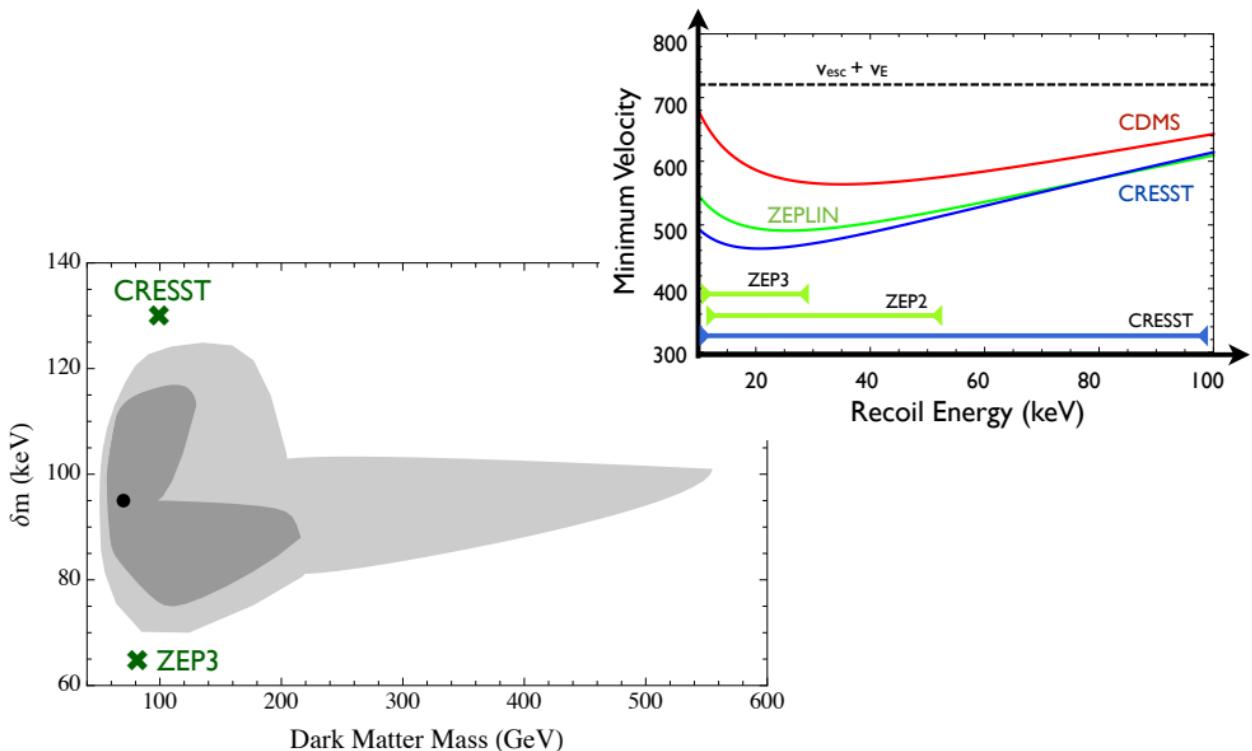
Parameter Space



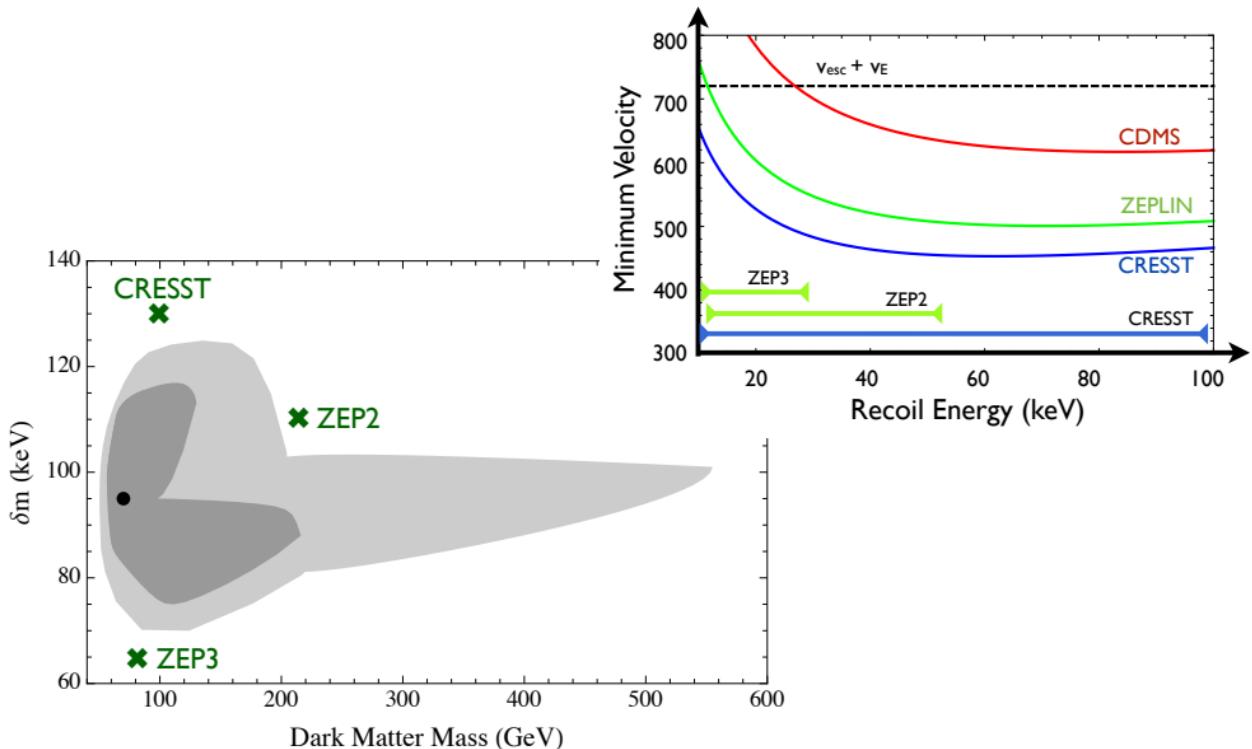
Parameter Space



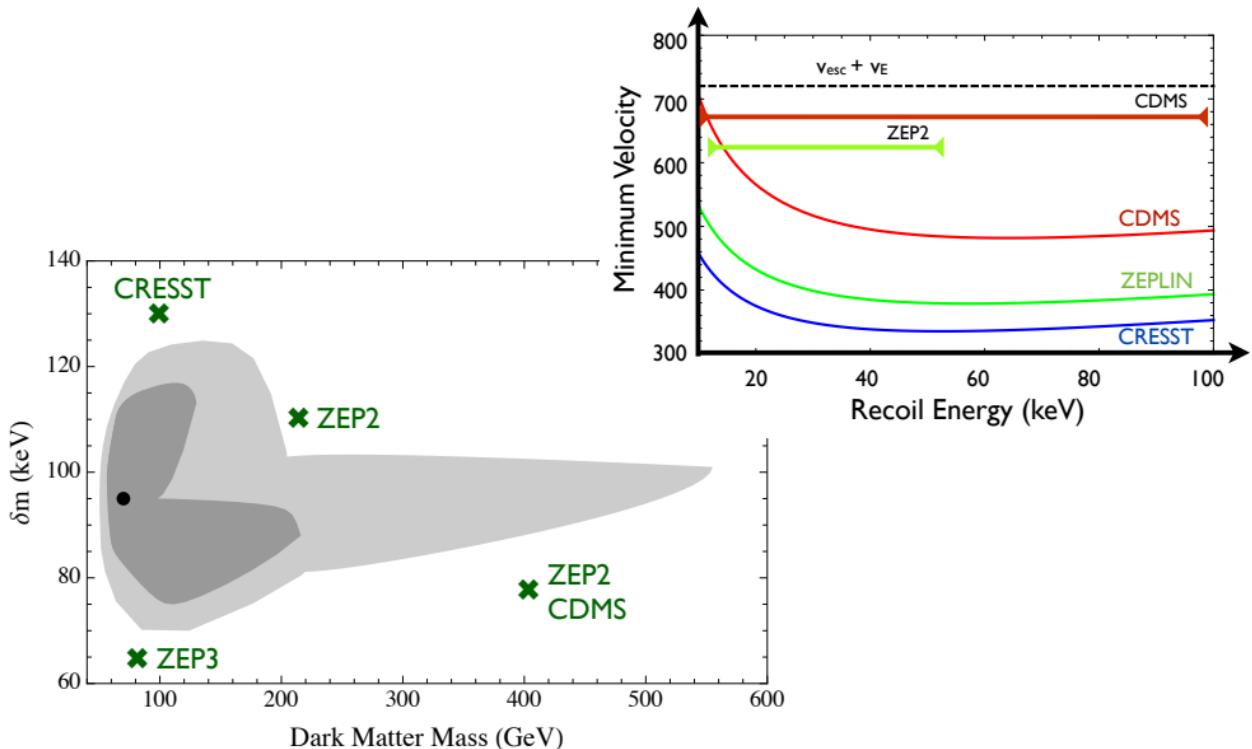
Parameter Space



Parameter Space

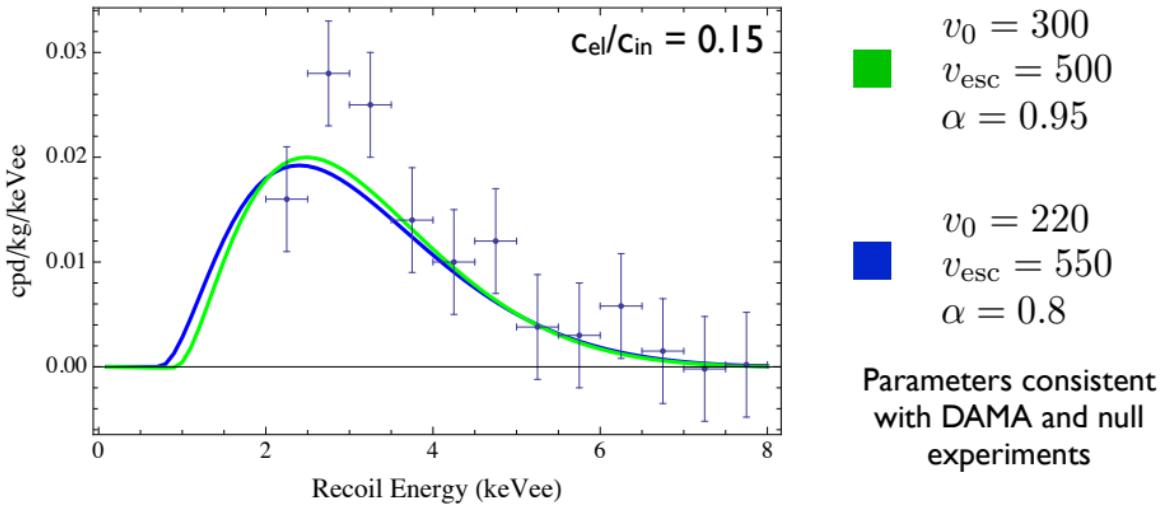


Parameter Space



Correlations

The same model, but with different halo profiles...

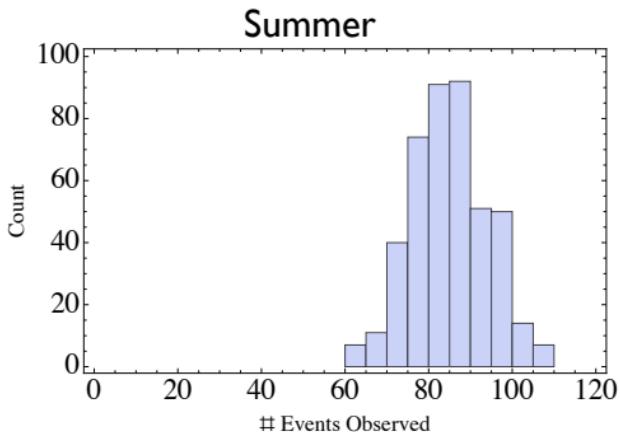
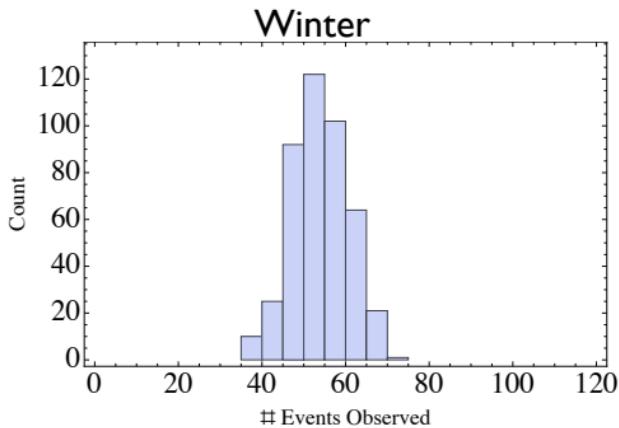


...cannot distinguish astrophysics parameters!

LUX/Xenon100

100 kg liquid Xe detectors (upgrade for Xenon10)

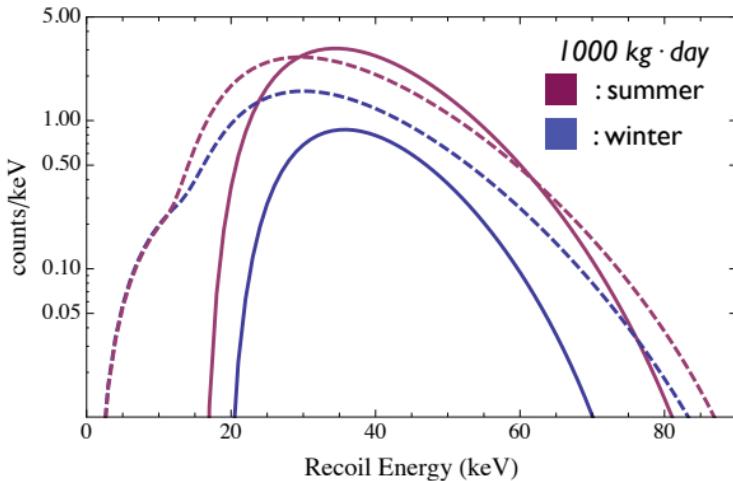
Can see a large number of events



(1000 kg-day exposure ~ 1 month!)

LUX/Xenon100

Recoil Spectrum



Elastic subcomponent most apparent near the energy threshold

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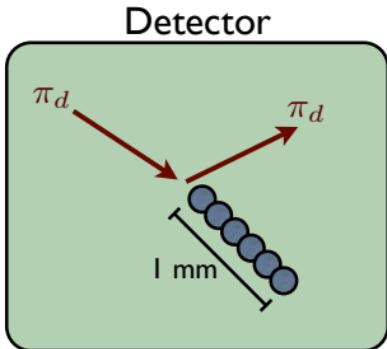
Uncertainties in halo profile

Direct Detection

Directional Detection Experiments

Directional Detection

Experiments



Good angular resolution requires sufficiently long tracks (~ 1 mm)

Head-tail discrimination requires large threshold energy (~ 50 keV)

CF₄: DMTPC, NEWAGE, MIMAC
CS₂: DRIFT

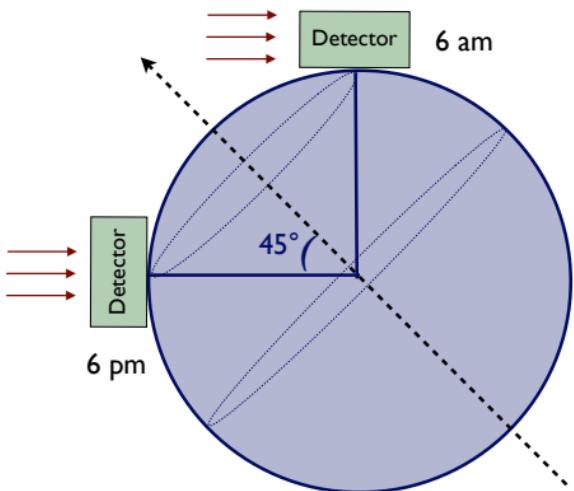
}

Need heavier nuclei to see inelastic signal!
Iodine (A=127) or Xenon (A=131)

Finkbeiner, Lin, and Weiner (2009).

Directional Detection

Motivation



Daily Modulation

Wind direction changes every 12 hrs

Large Amplitude

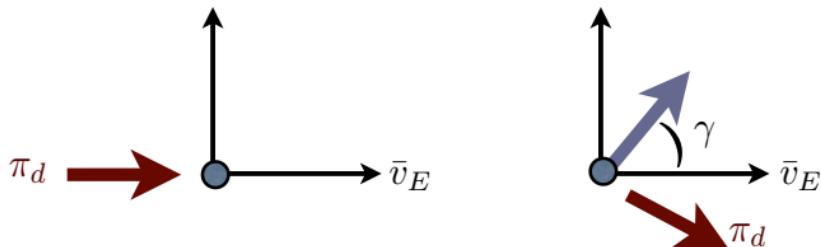
Daily modulation amplitude $\sim 100\%$

Smaller Backgrounds

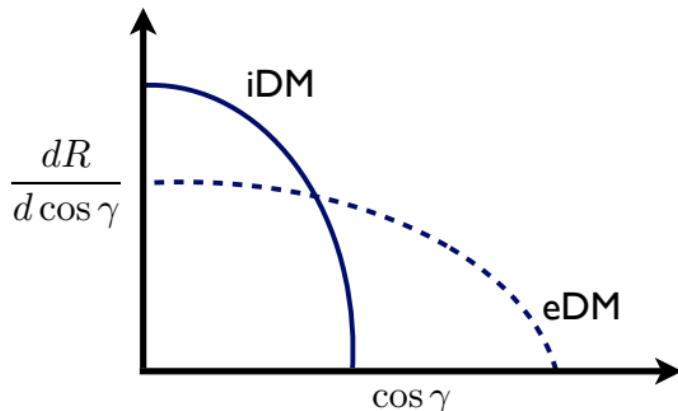
irreducible neutron backgrounds

Spergel (1988).

Directional Detection

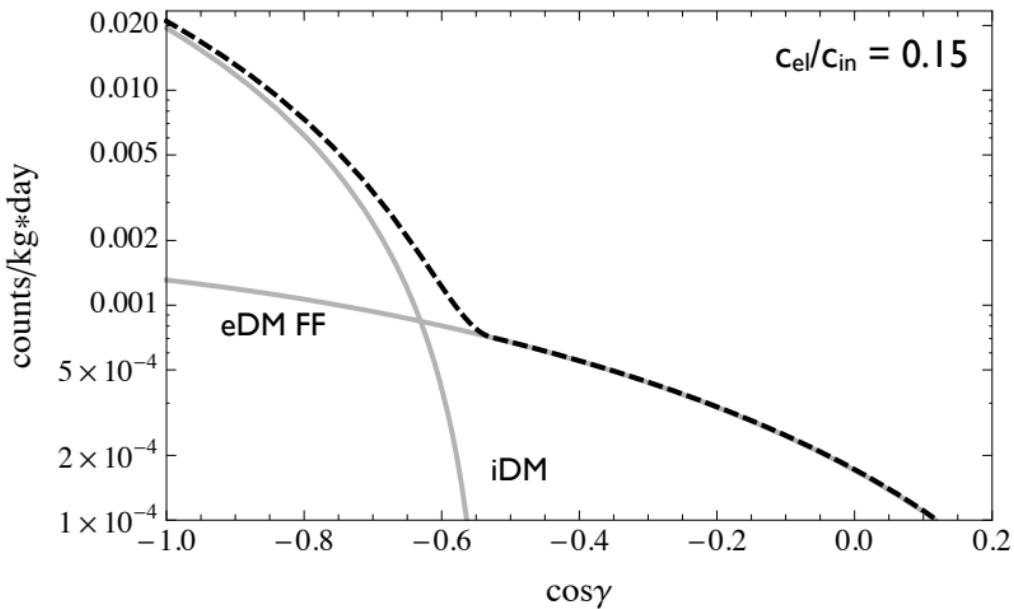


Different dynamics in dark matter sector result in different $\cos\gamma$ spectra

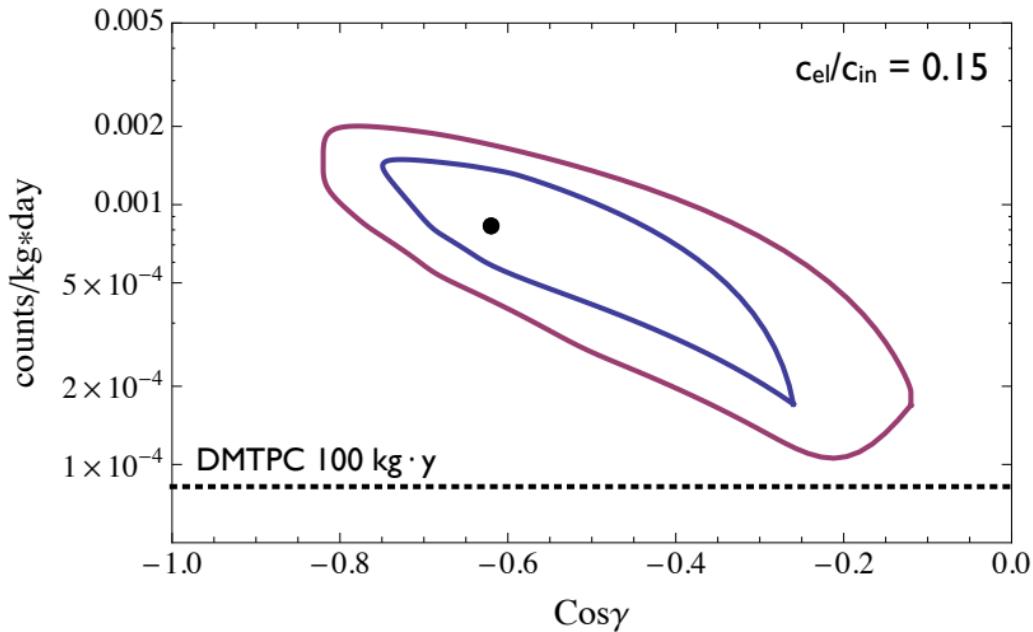


$$\cos\gamma \leq \frac{v_{\text{esc}} - v_{\min}}{v_E}$$

Directional Detection



Directional Detection



Conclusions

Composite inelastic DM can explain 100 keV scale

Parity violation leads to interesting scattering behavior

LUX/XENON100 can see many events

Directional detection needed to disentangle dynamics